SSRG International Journal of Electrical and Electronics Engineering
ISSN: 2348-8379/ https://doi.org/10.14445/23488379/IJEEE-V12I8P116

Volume 12 Issue 8, 173-185, August 2025

Original Article

Wind Power Maintenance Proposal Template for Virtual Training in the Formation of New Professionals with a Focus on Industry 4.0

Christian Carvajal[1], Monserrath Acosta[2]

[1]Pontificia Universidad Católica del Ecuador Sede Amazonas, Sucumbíos, Ecuador.
Instituto Superior Tecnológico CRECERMAS, Sucumbíos, Ecuador.
[2]Instituto Superior Tecnológico Martha Bucaram de Roldós, Sucumbíos, Ecuador.

[1]Corresponding Author : cc.andres9316@gmail.com

Received: 11 June 2025 Revised: 13 July 2025 Accepted: 12 August 2025 Published: 30 August 2025

Abstract *- This paper presents the structure of a wind maintenance proposal model for three-bladed horizontal-axis wind turbines. This proposal model uses virtual reality technology, allowing the user to work immersively on maintenance actions and tasks for the main components of the wind turbine. This program, called Simulwind, is a tool that offers a simulation environment of a maintenance room for a wind turbine model. The user works on creating tasks and digitizing processes that allow for interaction and inspection of components with the help of tools and safety equipment necessary to detect defects and troubleshoot. In this way, results are interpreted, making it possible to compare indicators between the proposal model obtained in virtual training and traditional maintenance strategies. Additionally, the proposal model applied to Industry 4.0 meets the training needs for new professionals involved in the maintenance of wind turbine components by working in real time. This way, breakdowns are prevented, and important indicators such as reduced maintenance costs and reduced human errors in procedures and task execution are achieved.*

Keywords *- Industry 4.0, Simulwind, Virtual Training, Wind Turbine, Wind Maintenance*.

1. Introduction

The use and access to alternative energy sources in society and the economic sector for energy production are currently essential and necessary. Agroindustrial development, national growth, and improvements in the quality of life have led to exponential growth in energy demand over the past 10 years. The use of fossil fuels for energy has been the main cause of climate change on our planet [1]. The development of the wind energy sector in countries like Germany, one of the European countries that dominates the alternative energy market, demonstrates that the wind energy sector has become an important part of the German economy. From an investment and operating cost perspective, the economic operation of wind turbines is essential [2].

Today's modern wind turbines are highly technologically advanced. Factors such as system size and performance also increase the load on individual system components. For this reason, maintenance and operation concepts must be developed that can extend the turbine's operational lifespan while simultaneously reducing costs for the operator [3]. Natural resources are gradually being depleted, signaling a shift in the search for sustainable, non-depleting, and environmentally friendly energy. China, the United States, Germany, and India are the four countries that dominate the wind energy market. Wind turbines on water or land generate electricity through the movement of the blades, transforming kinetic energy into mechanical energy [4].

As global energy demand increases considerably, the availability of natural resources decreases in parallel, reaching a point where there are not enough resources to meet the demands of an entire society. Therefore, in the not-too-distant future, the development of environmentally friendly energy sources, such as wind power, will be essential. It has the advantage of avoiding greenhouse gas emissions.

Wind farm maintenance, involving various work processes inside the turbine, reveals a large number of occupational hazards for personnel. The inexperience of operators is compounded by the lack of a maintenance strategy model that allows for advantages over traditional strategies. The project's need is based on the development of research that addresses in-depth topics related to Electronics and Automation. Its purpose is to meet the needs of the use of alternative energies and link them to digitalization processes focused on Industry 4.0. One of the problems to be solved is the increasing demand for energy consumption, which is making the availability of natural resources scarcer. Therefore, the use of wind energy is necessary, as it is an energy source with the advantage of not generating carbon dioxide emissions or producing waste.

As a final issue, the occupational hazards associated with working on wind turbines to perform maintenance, as well as the lack of experience among new personnel, necessitate the use of virtual training software to train maintenance professionals in various processes based on a new maintenance activity strategy model for the main components of a wind turbine. The importance of the research project lies in the benefits of virtual simulation. Working with wind energy offers several benefits, including renewable energy, non-polluting energy, and reduced use of oil, coal, natural gas, and liquefied petroleum gas. The virtual training process benefits the training of personnel who perform wind turbine maintenance, highlighting the reduction in occupational hazards caused by accidents during wind turbine maintenance work. Another key benefit this proposed model offers is the improvement of wind turbine maintenance activities. The objective is to implement and develop virtual training for maintenance tasks on a three-bladed horizontal-axis wind turbine based on a maintenance proposal model that addresses priority maintenance activities for the main components of a wind turbine. The objective is also to interpret the results to establish an equal or better comparison of indicators between the maintenance proposal model developed in the virtual training and traditional strategies. This highlights application programs such as Simulwind, a training tool for the digital age.

When establishing a methodological foundation for wind maintenance, the study of the behavior of systems linked to the man-machine context known as the Jenkins methodology stands out, which is characterized by having a technical scheme where its different components are in constant interaction with well-defined purposes [5].

By performing condition monitoring, vibration measurements, acoustic emissions data, oil analysis information, and other information, it is possible to obtain. Therefore, optimizing maintenance activities based on this relevant information, minimizing variable maintenance and operating costs, is one of the objectives of condition-based maintenance [6]. Factors such as geographic locations, seasonality, and availability of logistics, transportation equipment, skilled labor, travel expenses and materials are very important to analyze when performing maintenance on wind turbine blades. This element is one of the main components of the wind turbine, and several maintenance elements are important when developing these factors [7]. The efficient operation and maintenance of wind turbines is the result of a failure analysis in the turbine, observing and detailing the elements or components with said failure [8]. One of the maintenance simulation models we have developed is a project developed at a wind turbine farm, resulting in optimized maintenance and minimized costs. Strategically speaking, it is analyzed with respect to a combination of yaw system failure data and wind speed [9].

Another related work is that of Srikanth Nandipati, who discusses the use of reliability parameters calculated from field data for multiple defect groups to formulate multiple maintenance plans and then consolidate them into a single cost-effective maintenance plan. Similarly, the work of Amith Nag Nichenametla attempts to leverage the broad range of predictive analytics techniques used in the wind energy sector to address these challenges and remain competitive in the market. Yoel David Pernía Mora presents an overview of the components of a wind tower. Typical operating problems are addressed. The types of maintenance performed on wind turbines and the concepts currently being applied to increase their availability and reduce operating costs due to unscheduled downtime are explained. Bharat Kumar conducted an analytical study related to wind turbine failures for a wind farm in Devgarh, Pratapgarh district, Rajasthan, India. Among other works, Abeer Amayri presents an article on the development of condition-centered maintenance for wind turbine systems, considering the economics and dependence of different types of wind generators.

Among the statistics on wind farm maintenance, reactive strategies account for 60% of breakdowns present in the mechanical system, such as gears and bearings that occur due to breakage or wear of the material, misuse of oil, oil at high temperatures, vibrations, etc. The height at which the wind turbines are placed makes them prone to the impact of lightning on the structure of the system, creating an electric arc that extends through all the components of the wind turbine, reaching temperatures of up to 30,000 ℃, in this way these atmospheric problems represent 20% of the damage caused to wind turbines [5].

Additionally, other statistical parameters indicate that 10 lightning strikes a wind turbine's blades annually. The mechanical systems housed within the turbine handle up to 400 liters of lubricating oil, which, as a result of lightning strikes, short circuits, and sparks, can cause fires. These represent 7% of all failures and the loss of the wind turbine, resulting in very high costs. Material fatigue is a slow deterioration caused by the stresses that occur in mechanical systems, with compression or impact damage being noted in the gear systems. Gears, bearings, blade orientation systems, and nacelles are prone to abrasion, adhesion, and wear, known as tribological phenomena. Physical-chemical reactions, such as corrosion of the system's metallic structure and polymer deterioration manifested by sun exposure, affect hydraulic systems, cable insulation, and other metallic parts [5]. In the vision of Industry 4.0 in industries with a tendency toward process digitalization, a tool has emerged for the training of new professionals linked to the wind sector that allows for the early detection of faults in the main components of wind turbines. To this end, Simulwind is an instrument that meets the aforementioned parameters as a simulation software highly adaptable to the training needs of users and professionals in charge of wind turbine maintenance and operation [10].

2. Maintenance and Operation Concepts

2.1. Traditional Maintenance Strategy in Wind Turbines

The maintenance strategy in offshore energy is evolving; while in onshore wind energy, the strategy is dominated by preventive maintenance, which is closely related to the instructions in the original wind turbine manufacturer's maintenance manual, but is affected by unscheduled shutdowns [11]. Traditional maintenance on wind turbines is based on scheduled shutdowns to perform tasks related to the replacement of certain components due to the exhaustion of their considered useful life. Current maintenance on wind turbines is based on analyzing the equipment's preconditions to decide on actions that minimally affect production. Figure 1 describes traditional maintenance strategies for wind turbines.

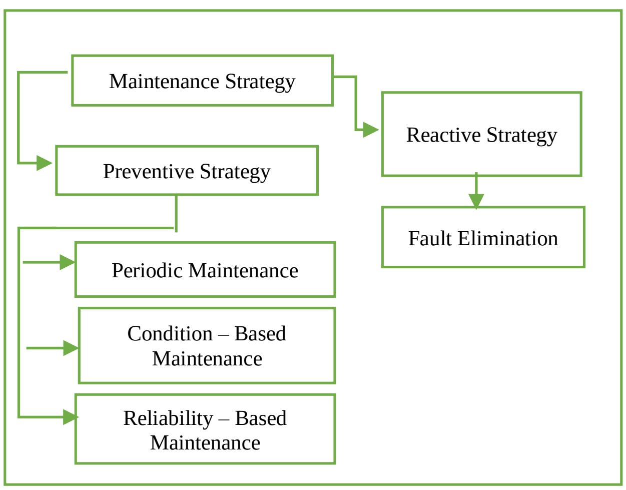

Fig. 1 Schematic description of the various types of maintenance

2.1.1. Preventive Strategies

It is understood as the set of activities scheduled in advance to reduce the frequency and impact of failures [11].

2.1.2. Reactive Strategies

It involves eliminating breakdowns. For example, 60% of breakdowns are found in the mechanical system, such as gears and bearings, either due to breakage or wear of the material, misuse of oil, oil at high temperatures, vibrations, etc. The height at which wind turbines are located makes them prone to lightning striking the system structure, creating an electric arc that spreads through all the wind turbine components, reaching temperatures of up to 30000 ℃. These atmospheric problems represent 20% of the damage caused to wind turbines. Certain statistics indicate that 10 lightning strikes strike wind turbine blades annually. The mechanical systems housed within the turbine handle up to 400 liters of lubricating oil, which can cause fires, representing 7% of all failures. These are caused by lightning strikes, short circuits, and sparks. During maintenance work, it is very difficult to access the nacelle at such a height, which is why the loss of this wind turbine represents very high costs. Material fatigue is a slow deterioration caused by the stresses that occur in mechanical systems, with damage due to compression or impact in the gear systems being noticeable. Gears, bearings, the blade orientation system, and nacelles are prone to abrasion, adhesion, and wear, known as tribological phenomena. Physical-chemical reactions, such as corrosion of the system's metallic structure and polymer deterioration manifested by sun exposure, affect hydraulic systems, cable insulation, and other metallic parts [5].

2.2. The Hierarchical Asset Tree of a Wind Farm

It consists of classifying the assets of a wind farm and grouping them based on a hierarchy. This provides a structured view of all the assets comprising the plant. This allows for advantages such as facilitating the search for an asset to perform a specific maintenance task and the development of a maintenance plan for the wind farm. Another advantage is that indicators such as costs, availability, statistics, and work orders really contribute to decision-making.

2.3. Hierarchical Levels

They are a set of items that make up a wind farm based on a classification criterion. There are six hierarchical levels: Center or park, area, system, subsystem, equipment, component, or spare part [12].

2.4. Online Diagnostic Techniques

It consists of performing a diagnosis based on data obtained online from instruments installed in the control system, which are sent to those responsible for direct readings. The reading can be done in the field using the indications of the instruments used to analyze the data in a more complex and detailed manner. Data can also be captured manually in the control room, offering convenience in data collection.

Another way to capture data is automatically, known as the data logger principle. Data loggers are connected to the instruments and remain connected as long as possible, storing data for later analysis. The most complex and effective approach involves investing in equipment and developing software for automatic mathematical analysis of data from the control room [13].

2.5. IRIM Protocol 202410

Published in 2017, it shows the minimum tasks to be performed on a wind turbine, regardless of its brand.

Maintenance is based on a quarterly inspection of the wind turbine. It also seeks to avoid the constant increase in the gearbox that results from wind turbine downtime with a semi-annual inspection. One of the bases of the protocol is that all tasks are performed by electromechanical professionals with knowledge of instrumentation. There are two types of inspections based on their frequency: one is performed quarterly, with approximately 3 hours of work per wind turbine, with a visual inspection of points within the nacelle, on the tower, and even on the foundation. The other inspection is annual; it is performed with such frequency because the faults they are capable of detecting have a much longer generation period [12].

2.6. Offline Diagnostic Techniques

Its fundamental basis is condition-based maintenance, which allows for the observation of equipment to determine the condition of components and determine whether or not maintenance intervention is necessary. A work order is created for the scheduled intervention of a group of technicians who will have the least impact on production, in aspects such as component cleaning, adjustments, and lubrication [13].

2.7. Industry 4.0 and Maintenance

Maintenance plays an important role in the fourth industrial revolution, as it works with the principles of anticipation, efficiency, and effectiveness of the smart factory. Machine monitoring is nothing new, but in the context of Industry 4.0, this process allows for the collection of data generated by sensors incorporated into the machine. Appropriate modeling and processing techniques allow the data to be transformed into useful information that lends great importance to the maintenance process, especially predictive maintenance. Thus, the technological developments of Industry 4.0 will enable the full integration of the value chain, from the customer involved in product design to after-sales service, through versatile and intelligent technological systems [14].

Industry 4.0's challenge is to find ways to interconnect existing processes through the use of technology that connects machines, people, equipment, and operations. The goal is to make maintenance simpler and easier to control and monitor operations. It considers it important to develop key concepts such as preventive maintenance, predictive maintenance, big data, artificial intelligence, the Internet of Things, cloud computing, integration systems, autonomous machines and systems, additive manufacturing, cybersecurity, virtual environment simulation, and augmented reality [15].

2.8. Applications of Virtual Reality and Augmented Reality in Industry 4.0

2.8.1. Design Optimization

The manufacturing processes for plastic, metal, or ceramic products, known as industrial prototyping, require high investment costs, making it necessary to physically create products to appreciate their characteristics and design. However, with the advent of virtual reality, the costs associated with modeling tasks are reduced, as this technology allows the creation of products in a close-to-realistic simulation to analyze their characteristics and designs.

Furthermore, augmented reality is useful for the assembly and design of facilities, as it provides additional information that appears to the technician on hands-free devices to determine whether the actual dimensions of the factory where the project will be installed are considered adaptable [16].

2.8.2. Plan Maintenance and Control

When a breakdown occurs, the operator typically does not have the machine's instruction manual on hand to perform the maintenance operation, resulting in lost time when the plant has to stop production until the manual or a professional with knowledge of the machine's operation is found. With augmented reality, the operator dons the vision glasses and, through them, follows the detailed steps in the virtual instructions projected onto the lens to resolve the fault [16].

2.8.3. Operations Training and Operator Training

With virtual reality headsets, placing an operator in a simulation of a machine that has stopped production is possible, allowing them to perform relevant inspection and maintenance tasks as if they were working in a similar, real-life plant environment. Therefore, virtual reality is a technology that allows companies to train their operators in an optimal and cost-effective manner, eliminating training costs for technical staff, reducing time, and avoiding machine downtime [16].

2.8.4. Assistance and incident resolution

The remote assistance application, provided by expert technicians using augmented reality, guides factory workers through the maintenance process. With the glasses and integrated camera worn by the operator, the connection with the machinery manufacturer's technical service is a success. This optimizes production times by avoiding long downtimes until technical service personnel arrive. It also represents cost savings in travel expenses and the work hours of maintenance service professionals [16].

3. Materials and Methods

This paper aims to implement and develop virtual training for wind turbine maintenance tasks based on a maintenance proposal model that addresses priority maintenance activities for the main components of a wind turbine. It also aims to interpret the results to establish an equal or better comparison of indicators between the maintenance proposal model implemented in virtual training and traditional strategies. It highlights application programs such as Simulwind, a training tool for the digital age. Research uses iterative and incremental development, so the project is planned in various time blocks. When we talk about iterations, we work on mini-projects to provide a complete final project. Each iteration seeks to improve task conditions, improving ideas as the mini-projects are completed based on the results obtained. Some benefits are presented, such as increased expectations, since the users do not know what they need when they see the project results. With the first iterations, important data can be obtained for the development of the next iteration. Simulation is more conveniently accessible for making minor changes in each iteration. Project complexity is managed, and the number of errors is minimized, gradually improving quality. The iterative and incremental methodology consists of training, development, and integration phases. The training phase consists of researching and studying the tools that make up the wind maintenance simulator. The development phase consists of meeting project requirements by performing iterations and creating maintenance tasks in the simulator. The integration phase consists of implementing the maintenance tasks in the virtual environment with trial and error testing that verifies the correct functioning of the implementations [17].

3.1. Research and Study of Tools

Simulwind version 1.38 is a virtual simulation program for wind turbine maintenance that, when downloaded, comes bundled with Unity and an executable file for Blender. Unity version 2018.3.7.1F is the simulator's engine software, developed with a series of programming routines created by MONSUTON. These routines allow users to experience an interactive environment, considered a video game or virtual environment of the wind turbine maintenance room. Blender version 2.8 also includes an executable file containing the 3D model of a horizontal-axis three-blade wind turbine, including 50 parts or blocks. It has all the components that are going to be assembled and disassembled in the maintenance processes and integrates the nacelle and the hub located in the rotor, which is responsible for holding the blades and connecting them to the main axis of the electric generator to visualize them in a realistic way with all the selected components, integrated into groups and subgroups for the maintenance of the wind turbine [18]. Simulwind users exclusively benefit from the benefits developed by MONSUTON, and proceed on their own initiative to create and implement maintenance tasks under the new maintenance proposal model.

3.2. Wind Power Maintenance Proposal Template

Simulwind Competitiveness in maintenance processes is one of the reasons why the proposal model must be efficient and meet the company's needs in reducing maintenance costs. With proper management and efficient analysis of the company's needs, the required maintenance activity guarantees excellent results in production systems and minimizes company costs. The company's available resources and their management allow for an efficient model for adequate planning of maintenance areas in operational and strategic work. The structure of the maintenance model is based on the analysis of information obtained during the operational maintenance of wind turbines in various studies, which present technological and digitalization challenges. The presented model is sequential and orderly, considering tests that determine the most important actions, taking into account the safety of maintenance and operations personnel. Furthermore, virtual training is one of the main pillars of the training and development of wind turbine maintenance technical personnel.

3.2.1. Analysis of Traditional Strategies

The first stage of the model consists of analyzing traditional maintenance strategies for wind turbines. Figure 1 highlights a preventive strategy model to reduce the frequency and impact of failures and a reactive strategy to eliminate outstanding failures in the mechanical system. Table 1 shows the failure modes and their causes.

Table 1. Failure modes and main causes in a wind turbine

Failure Modes	Root causes of failure
Structural Failure	Design defect
Electrical failure	Material defect
Mechanical failure	Installation defect
Software or control failure	Maintenance defect
Insulation failure	Software defect
Thermal failure	Corrosion
Mechanical attack	Misalignment
Bearing failure	Low-cycle fatigue
Component fracture or material failure	High-cycle fatigue
Joint failure	Mechanical wear
Contamination	Lack of lubrication
Blockage	Thermal overload, electrical overload, weather incident, grid incident

The high risk involved in working at heights, handling heavy weights with high-tonnage cranes, electrical hazards, and confined spaces such as those between generators, gearboxes, and geared motors, where there is a risk of jamming and accidents, are considered high-risk activities [5]. The causes of failure that occur in the main components of Wind Generation Systems are then analyzed in Table 2.

Table 2. Causes of failure in wind turbine components

Subsystems	Causes
Electrical System	Due to component fatigue, poor cable connections, consequences of other alarms, line tripping due to an electrical storm, a faulty contactor, inefficient retightening of connections, and poor sizing of equipment based on nominal capacity

Power Electronics	Faulty contactor, electrical storm, short circuit in power unit, chained component failure, line overvoltages and currents, and electrical storms.
Sensors	Real alarm warning, due to poor sensor adjustment, sensor misalignment due to operation, adverse conditions (temperature, weather, etc.), poor transmission due to dirt, and low quality of components
Hydraulic System	Leakage in pressure and flow systems, mainly due to oil degradation
Orientation System	Bad sensor information, faulty feedback system, poor reference adjustment, and lack of lubrication
Blades – Hub	Weather conditions, bird strikes, lack of system lubrication, and poor main shaft alignment
Mechanical Brake	Due to a lack of lubrication of the hydraulic system, the disc cannot be ground.
Generator	Overcurrent due to load variation during operation, phase-to-phase shunt, poor cable connection, brush wear, defective rotor contactor, inefficient retightening, lack of lubrication, poor connection at output terminals
Gearbox	Poor connection in hydraulic cooling and filters, poor application of anti-corrosion paint
Nacelle	Weather conditions, oil spill

3.2.2. Continuous Improvement with a Focus on Industry 4.0

An analysis of traditional strategies reveals a technological need for the use of virtual training tools to train new wind turbine component maintenance professionals, enabling acceptable learning and practice rates. These values are very important for addressing human errors that represent risks to the company's production and costs. The proposed model is closely related to the Total Productive Maintenance (TPM) approach, as industries are currently more technologically and economically competitive, with various objectives related to indicators such as, for example, cost and time reduction, knowledge expansion, and staff training.

This model is distinguished by working for the common benefit and efficiency of the company, with the support and collective effort of all technical and administrative staff, with the common goal of avoiding any type of losses in the aforementioned departments. Among the applications of Industry 4.0, they indicate that the simulation of virtual environments allows for the reduction of costs associated with learning processes with the virtual representation of the wind maintenance plant, such that operators can test different configurations until achieving optimal equipment performance and exchange experiences in the real world to improve the configuration of the virtual environment [19]. Furthermore, augmented reality enables plant maintenance and control, with maintenance instructions guided through virtual devices, enabling operational training and operator training. Guided assistance provided by expert technicians optimizes production times by avoiding long machine downtimes [18].

Therefore, Total Productive Maintenance (TPM) and Industry 4.0 are closely related in the sense that the main contribution of TPM is the training of the person in charge of the operation, who intervenes in the equipment when failures occur and maintains the component in optimal operating conditions, thus allowing the user to improve the degree of positive attitude to detect potential problems that may damage the equipment [5]. With Industry 4.0, virtual reality is a technology that allows companies to train and educate their operators, eliminating training costs for technical personnel and reducing machine downtime [16].

3.2.3. Maintenance Support

Maintenance actions in Industry 4.0 are important, as they aim to minimize the visual and economic impact of the product, as well as develop a new model with methodologies that consider the impacts of maintenance, enabling the transition toward sustainability where Industry 4.0 can drive sustainable manufacturing through real-time information on process and component conditions [20]. The proposal model of this paper is based on a preventive, corrective and update maintenance strategy as detailed in Figure 2.

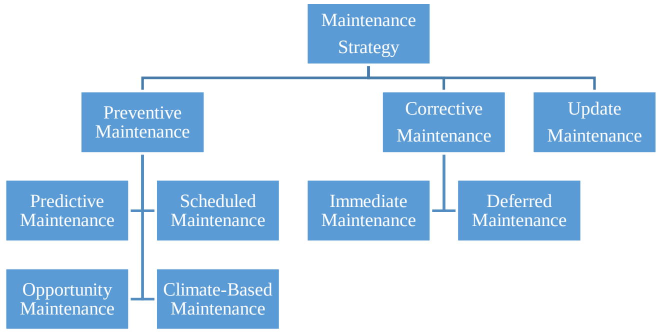

Fig. 2 Maintenance strategy

The strategy based on preventive maintenance aims to ensure the reliability of the equipment before any failure or breakdown occurs, thus avoiding machine downtime [5]. This proposal model is considered because the failure of any component during maintenance can lead to loss of life, so preventive maintenance is essential to avoid failures and unviable costs. This ensures high performance and reduces unplanned downtime, maximizing the equipment's useful life. It carefully integrates other maintenance tasks to measure turbine component wear with monitoring, establishes a periodic maintenance program, takes advantage of equipment downtime to review potential failures in wind turbine components, and notes the influence of meteorological factors such as weather. Since component failures are unforeseen, corrective maintenance is important in the model, as corrective actions cannot be planned, nor can a required budget be calculated. Therefore, it is very important to have a wide selection of tools available to users to take immediate action, or once a failure occurs, to shut down the machine to stock up on the necessary resources and materials for repair.

Finally, a maintenance update involves the use of a software development project known as SIMULWIND. This tool allows for interaction with the virtual environment in a wind turbine's maintenance room and with the components requiring maintenance. This tool utilizes personal protective equipment, work tools for handling parts, and consideration of teleportation points called portals. The sequential steps comprising the list of practices and exercises involve user interaction with the 3D wind turbine model while inspecting the objects and components considered in the virtual environment.

3.2.4. Creating Maintenance Tasks

For the creation of maintenance tasks in Simulwind, the code used to structure content is Hypertext Markup Language (HTML). It should be noted that HTML is not a programming language; rather, it is a markup language that defines the structure of content. Therefore, HTML consists of a series of elements used to enclose content structures that are viewed or behave in different ways. The use of enclosing tags allows for changing words to italics, making fonts larger or smaller, etc. Among the main programming considerations, HTML color coding was used for better visual interaction with the user. Table 3 shows the list of maintenance tasks created in the simulator based on the maintenance proposal model, and among them, the tasks that facilitate interaction with the software are used. The maintenance tasks and practices are based on priority actions on wind turbine components such as the Braking System, Blade Orientation Mechanism, tower maintenance, gearbox, generator, rotor, and mechanical transmission system.

3.3. Implementation and Testing of Virtual Training

The implementation of wind turbine maintenance practices is carried out on the main components with the procedure, actions and steps implemented for each of the tasks considered in Table 3.

Three important aspects stand out. First, as shown in Figure 3, the Preliminary Instructions provide information for starting the simulator. The user can select the practice to be performed and the difficulty level, ranging from low, medium, and high. In other words, they address the style of assistance provided for each practice.

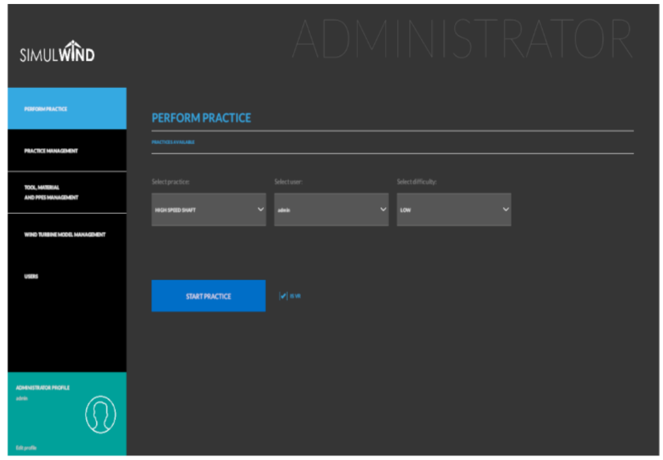

Fig. 3 Preliminary instructions

The second important aspect is Exploration and Equipment, as shown in Figure 4, which has to do with the commands for movement in the virtual environment and the interaction in the maintenance room with personal safety equipment.

Fig. 4 Exploration and equipment

Finally, the third important aspect is the Development of the task, as shown in Figure 5, based on the list of steps that the user must follow to complete the maintenance actions on the wind turbine.

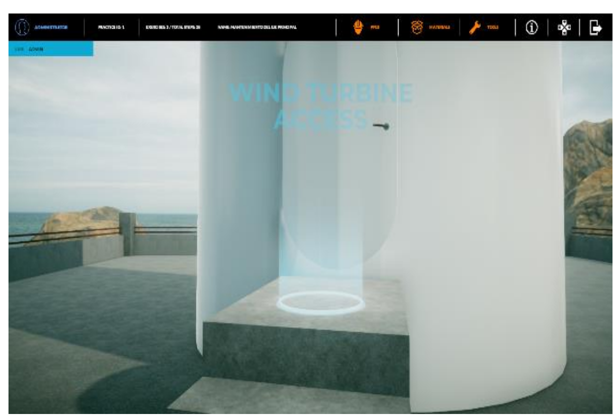

Fig. 5 Development of the task

Table 3. List of Maintenance Practices in Simulwind

List of Practices	Exercises	Tasks
Braking System	Wind Turbine Shutdown. Yaw Control Programming. Slow Shaft and Rotor Check. Fast Shaft Braking and Lubrication	Check the bolt torque. Check the condition of the calipers and brake pads. Check the brake disc. General Lubrication Check the driveshaft.
Blade Orientation Mechanism	Pitch Control	Check the drive motor Check the lubrication levels Check for possible oil leaks Check bearings, pinions, and gears Check all hardware In the hydraulic system, check for levels and leaks, and change the filter when necessary.
Tower Maintenance	Door Inspection. Inspection of the lower part of the Tower. Inspection of the middle part of the Tower. Nacelle, casing, crown	Verification of the gondola to the tower Exterior appearance (protective paint) Anchoring to the base
Gearbox	Gearbox Inspection	Check surface oil Check couplings Check mounting hardware
Generator	Check the general appearance of the generator's exterior Check the anchors	Check the general appearance of the generator's exterior Check the generator's anchoring
Rotor	Visual inspection of the assembly. Detection of cracks and breaks in the hub and blades. Inspection of the surface condition of the blades. Inspection of the blade adjustment system. Tightness of the screws in the blade adjustment system.	Visually inspect the rotor assembly. Check for cracks and breaks in the rotor assembly. Perform a sensory check of the main shaft. Observe the surface condition of the blades. Inspect the mechanical element of the blade adjustment system. Inspect the tightness of the mechanical element of the blade adjustment system.
Mechanical Transmission System.	Position and lubrication of the slow shaft. Position and lubrication of anchors and couplings	Bearing location Coupling location Anchor location Lubrication

3.4. Simulation Parameters and Characteristics

Table 4 describes the important parameters for the simulation.

Table 4. Simulation parameters

Parameter	Description
Component to train:	Braking System, Blade Orientation Mechanism, tower maintenance, gearbox, generator, rotor, and mechanical transmission system.
Difficulty level	Low, Medium, High
Task Step List	A sequence defined in the programming for the creation of each task
Actions for each task	Inspect, select tools, combine materials, apply torque, etc.
PPE required	Protective helmet, gloves, harness,
Enabled resources	Tools, materials, and objects of the 3D wind turbine model
Navigation points	Teleportation points, gondola access to tower, etc.
Initial conditions	Equipment status, brakes applied, mechanical lock, alarms.
Evaluation criteria	Completion time, number of errors allowed, mandatory steps, order and sequence of execution.
Teaching aids	Guide videos, text instructions, and ambient sound

Table 5 describes the simulation characteristics.

Table 5. Simulation Characteristics

Parameter	Description
Standardized flow	A general and specific flowchart is followed for each component with its respective maintenance action.
Guided interactivity	Step-by-step validation. You cannot advance to the next step if you do not have the appropriate personal protective equipment.
Performance metrics	Record of times per step, errors, sequence compliance and PPE.
Immersive environment	Navigation is in the maintenance room and within the wind turbine, with access to teleportation points.
Closing instructions	Final videos and learning verification checklist

4. Results and Discussion

4.1. Operation and Maintenance Costs

Wind farms have equipment that requires continuous monitoring and maintenance. Operation is monitored on computers to store important data such as temperatures, electrical values, vibrations, and alarms.

In South America, a 30 MW wind farm has more than 10 wind turbines, where breakdowns are more common.

For the operation and maintenance of a wind farm, the minimum personnel required per wind turbine is two people: one plant manager (engineer) who is responsible for coordinating operations and maintenance, four operating technicians, and one administrative technician. Table 6 shows the Operating Personnel Costs for a 30 MW plant.

Table 6. Costs for a 30 MW plant considering

Description	Amount	Monthly Salary (USD)	Annual cost (USD)
Plant Manager (Engineer)	1	2300	37674
Operator (Senior Technician)	4	1200	78624
Administrative Technician	1	800	13104
Plant Manager (Engineer)	1	2300	37674
Total			129402

Table 7. Administrative costs

Description	Annual cost (USD)
Security	10190
Vehicle	7600
Insurance	210000
Grounds Maintenance	10500
Office Supplies	3000
Security	10190
Total	241290

For wind farms, a maintenance and uptime guarantee contract is typically signed with the wind turbine manufacturer. The maintenance service covers scheduled maintenance, repairs, consumables, and spare parts, the costs of which increase with age. Wind farm maintenance costs are considered variable costs due to the moving parts of these machines.

Therefore, maintenance work is related to the time and intensity of use, directly influencing production levels. Therefore, for a 30MW park, an external maintenance contract is estimated to be around $565.013. For a 30MW wind farm, the administrative costs are in accordance with the resources shown in Table 7.

Table 8 presents a summary of costs for the 30 MW park, which determines that of the total annual cost of USD 935705, USD 18714.1 are allocated for training [21].

Table 8. Costs of traditional maintenance strategies

Description	Traditional Strategies Annual Cost (USD)	Investment in Training (USD) 2% of the Total
Operation Costs	129402	
Maintenance Costs	565013	
Administration Costs	241290	
Total	935705	18714.1

The proposal model's maintenance strategy relies on maintenance support software to facilitate wind turbine inspection to determine the machine's condition while it is operating. Thanks to technological advancements focused on Industry 4.0 with virtual environment simulation, information is interpreted and utilized, helping companies anticipate and reduce failures for prompt repair. Table 9 details the investment costs for virtual training using the proposal model, which considers the use of high-end computers and virtual reality equipment such as headsets and controllers at USD 12000, plus instructor salaries of USD 4800.

Table 9. Proposal model maintenance strategy costs

Description	Amount	Unit Value/Salary (USD)	Investment for Virtual Training in the first year (USD)
PC with a high-end or better graphics card or video card	4	2700	10800
Virtual reality headset: Oculus Quest 2	4	300	1200
Training personnel	1	1200	4800
Total			16800

Table 10 establishes the training costs for wind turbine operation and maintenance using traditional strategies at USD 18714.1, which represents 2% of the total annual costs incurred by the German company Deutsche Gesellschaft für Internationale Zusammenarbeit for the Technical Assistance Program based on Alternative Energy. It also establishes the investment costs for virtual training using the equipment proposal model, plus instructor salaries of USD 16800 in the first year. For the second year, the investment using the proposal model is based exclusively on the payment of instructor salaries for four training sessions per year, which represents USD 4800. A comparison of the values for these strategies shows a savings of 10.22%, equivalent to USD 1914.1, in the first year, and a savings of 74.35%, equivalent to USD 13914.1, from the second year onwards.

Table 10. Cost comparison between maintenance strategies

Description	Traditional Strategies Investment in Training (USD)	Proposal Template Training Investment (USD)	Savings (USD)
1st year	18714.1	16800	1914.1
2nd year	18714.1	4800	13914.1

4.2. Wear of Wind Turbine Components

On the one hand, the wear of the wind turbine components, such as the hub, blades, tower and other external components, is due to physical phenomena, external agents, erosion and corrosion as seen in Figure 6.

Fig. 6 Wear on Blades

Furthermore, maintenance work requires training, so traditionally, the instructor and wind turbine maintenance technicians physically interact with tools and materials on wind turbine components countless times until the maintenance objective is achieved and errors are avoided. With virtual training, the instructor and wind turbine maintenance technicians interact with wind turbine components in a simulation process. This virtual process provides users with prior experience before their first physical interaction with wind turbine components during the required maintenance process. This means that the number of times a component needs to be disassembled is much lower than the number of times wind turbine components are currently disassembled, with the interaction of tools and materials that continually wear down the wind turbine. Table 11 compares the wear indicator of the components due to physical phenomena, the number of times of interaction with the component, and the economic cost.

Table 11. Component wear comparison

Traditional Strategies	Proposal Model
The effects of corrosion, erosion, and lightning affect components such as the blades, the hub, and the interior of the tower, among others.	Physical phenomena, in one way or another, will continue to wear down the external and internal components of the wind turbine.

The wind turbine component is disassembled countless times until the maintenance personnel are fully trained.	The wind turbine component needs to be disassembled less often because the user already has a virtual experience.

4.3. Time Spent on Maintenance Tasks

IRIM Protocol 202410 indicates that traditional maintenance task times are based on two types of inspections. The first consists of quarterly inspections, assuming approximately 3 hours of work per wind turbine. These tasks are based on the inspection of the elements that make up the nacelle, the foundation, and the underside of the wind turbine, such as verifying the tightening marks on the blade fastening bolts on the hub.

The second type of inspection is annual and involves tasks whose potential faults are being detected over a longer lead time, such as checking the tightness of screws on the gearbox cover. More than 90% of the tasks are sensory inspections, meaning inspections are performed on components by seeing, hearing, touching, or smelling. In addition to sensory inspection tasks, operational verification tasks are performed on the braking system, wind turbine startup, and pitch control, which regulates the pitch angle of the rotor blades. Finally, systematic tasks are performed, including greasing and lubricating certain components such as brake pads and anchors, or cleaning surfaces with tools and materials [12]. The proposed model for this work allows wind turbine maintenance technicians to constantly learn and practice within a virtual simulation environment. Iterations and repeated monitoring of maintenance tasks in Simulwind allow for faster work times than previous simulations. Table 12 indicates that the repetitive virtual training process in maintenance tasks allows technical maintenance personnel to reduce the interaction time with the real and physical components of the wind turbine since they have carried out several virtual simulation practices and are intellectually ready with the times and various adverse factors for their first real practice.

Table 12. Comparison of times in maintenance tasks

Traditional Strategies	Proposal Model
According to IRIM protocol 202410, the time spent inspecting each wind turbine ranges from 4 to 8 hours.	The inspection time for each wind turbine is estimated at 3 hours.

4.4. Levels of Preparation and Experience in Situations Involving the Handling of Tools Used in Wind Turbines

To determine the effectiveness of the virtual simulation proposal model and consider the results of wind turbine maintenance technical personnel familiarizing themselves with the software, a survey is required to validate the project. The wind turbine maintenance proposal model simulation was developed for technical professionals in maintenance, simulation, and control. A 10-question survey was then conducted for a total of 20 respondents, including professionals working in various companies and university students with knowledge of maintenance engineering and alternative energy, using the Google Drive Forms tool. Based on the results, Table 13 presents a summary of the percentages of affirmative or negative responses from respondents regarding the virtual training proposal model versus traditional maintenance strategies. An average of 91% of respondents agreed with the virtual training system.

Table 13. Results in percentage of the validation survey

Questions	Yes	No
1. Is the training system user-friendly?	95%	5%
2. Has your experience with the simulator been satisfactory?	80%	20%
3. Does the virtual environment have good graphics and realism?	85%	15%
4. Is the user's interaction with instruments and personal protective equipment satisfactory?	90%	10%
5. Is the guided training clear and understandable?	100%	0%
6. Is the simulation presented in the video adequate and presents all important parameters?	95%	5%
7. After using the training system, do you think you can achieve better results compared to traditional maintenance strategies?	90%	10%
8. Do you believe that the implemented procedure allows wind turbine maintenance personnel to achieve indicators with high levels of preparation and experience in handling wind turbine tools?	90%	10%
9. Does the simulator allow for obtaining a high indicator in the virtual manipulation of wind work operation tools?	95%	5%
10. Do you think the procedure implemented in this project increases the job safety of wind turbine maintenance personnel in the face of risky situations?	90%	10%
Average	91%	9%

4.5. Data Management and Informed Consent

4.5.1. Data Management

Data collected during the various virtual training tests, such as execution time, number of errors made, and performance levels, were used for academic research purposes, maintaining confidentiality throughout the entire process without individual identification.

4.5.2. Informed Consent

The respondent was informed in advance about the purpose of the practice, its procedure, and the academic use of the results during the simulation test. Participation was also voluntarily confirmed, as was the respondent's right to withdraw at any time.

4.5.3. Possible biases

Initially, all users were given instructions allowing them to develop difficulty levels in the simulator based on their familiarity with virtual environments and their experience with wind turbine maintenance.

4.6. Study Limitations and Future Research Directions

When conducting practical exercises in Simulwind, consider aspects and characteristics of the wind turbine 3D model objects that facilitate the interaction of their properties for the scheduling and creation of maintenance tasks. It is recommended that future work use Simulwind with the interaction of Blender and Unity in future versions to create other 3D wind turbine models that the user wishes to create for the study and research of Alternative Energy, different from the three-bladed horizontal-axis model loaded by default in the software. Consider the use of Simulwind in the study and application of other areas of knowledge, such as research on electrical and related machines, with information on the components and practices required for 3D modeling. Future work is recommended to compare implementation indicators that present task results between Simulwind and new virtual training software for wind turbines available online, considering new maintenance strategies and other virtual reality equipment. Better results were achieved with the maintenance proposal model due to several aspects, such as the benefit of working with free software, which allowed for freedom in programming to create maintenance tasks.

The customization of tasks and practices was key to allowing the user to improve the repeatability of maintenance actions in one way or another. Virtual training based on a horizontal-axis three-blade wind turbine model allowed for teleportation points with access to the different parts of the wind turbine. Safety standards, including the correct use of personal protective equipment, allowed for working with tools and elements very similar to those in real life. For this reason, work times were reduced, as were maintenance operating costs. Traditional strategies required a large amount of resources, while the proposal reduced costs thanks to the 4.0 approach to maintenance and training. Ultimately, virtual work resulted in less wear on the wind turbine components compared to traditional strategies, which suffered from greater natural wear and tear and from exposure to physical and climatic phenomena or situations, such as exposure to birds or lightning.

5. Conclusion

Necessary and important information was collected on current and traditional wind turbine maintenance strategies in sectors in the Americas and Europe that dominate the alternative energy market. It was evident that maintenance in offshore technologies is evolving; while onshore technologies are dominated by preventive strategies such as periodic maintenance, condition-based maintenance, reliability-based maintenance, and reactive strategies such as fault elimination, which represents 60% of wind turbine damage present in mechanical systems such as gears and bearings, due to either material breakage or wear. A wind turbine maintenance proposal model was developed with a structure based on Total Productive Maintenance (TPM), which takes advantage of the benefits of continuous improvement under the Industry 4.0 approach in virtual training of maintenance tasks on the main components of the wind turbine using "Simulwind" simulation software that meets the training need in the training of new professionals linked to the wind turbine operation sector.

Virtual training exercises were created using Hypertext Markup Language (HTML) in the wind turbine simulation software according to the proposed model for wind turbine maintenance activities and components. The exercises created in the software corresponded to maintenance tasks on the following: fast-shaft braking system, yaw control, blade pitch control, nacelle and casing maintenance tasks, tower maintenance tasks, gearbox tasks, generator tasks, rotor tasks (hub and blades), and mechanical transmission tasks (shafts, couplings). Each of the practices based on the proposal model was implemented and developed in the software, allowing the user to access virtual training in their training with maintenance tasks corresponding to the main components of the wind turbine. A comparison was made of indicators with equal or better results between the wind turbine maintenance proposal model and traditional strategies. For example, in the first year, the total cost of wind turbine operation and maintenance training of USD 18714.1 was reduced to USD 16800, equivalent to a savings of 10.22% with the proposal model, and in the second year, it was reduced to USD 4800, equivalent to a savings of 74.35%.

Wear and tear on wind turbine components is expected to be reduced with the proposed model, considering that the components are disassembled less frequently because the user has virtual experience handling tools and materials. This also means that throughout the wind turbine's useful life, the number of replacement parts and spare parts that make up the wind turbine components will be reduced. The maintenance task time for each wind turbine inspection proposal model is set at 3 hours, which is less than the maintenance time required for traditional strategies, which, under the IRIM 202410 Protocol, require an interval of 4 to 8 hours. The project validation survey showed an average of 91% of respondents accepting the virtual training system. The methodology used allows users to acquire high levels of training and experience in handling wind turbine tools. Respondents also indicated increased occupational safety and overall worker safety in the face of risky situations compared to traditional strategies. The benefits analysed with an Industry 4.0 focus indicate the company's efficient and collaborative work. Technically, the maximum performance of the equipment is leveraged with the virtual simulation program, which enables the training of wind turbine maintenance personnel to work on the equipment and establish optimal operating conditions for the wind turbine components. Simulwind is a training tool for wind farm sustainability that was selected due to its feasibility in acquisition costs (free software) and that allows the user to take advantage of the simulator's 3D model of a horizontal-axis three-blade wind turbine.

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